Cassini Spacecraft RTG's Power and Thermal Analysis During the 20 Year Mission

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Space Power Workshop 2018, Los Angeles, California

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- Cassini Power over time
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- Last Cassini Power, Thermal and Pressure Telemetry
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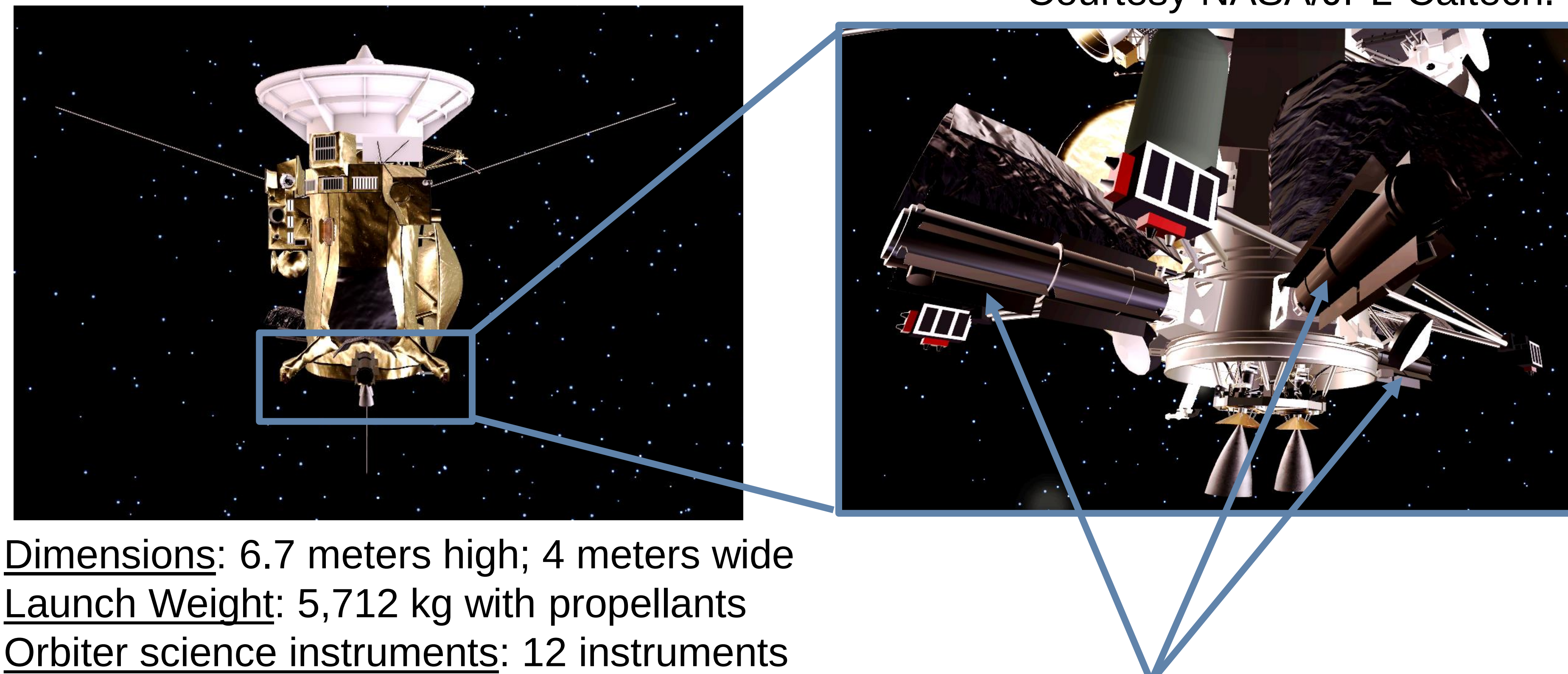
Cassini spacecraft and Radioisotope Thermoelectric Generators (RTGs)

Courtesy NASA/JPL-Caltech.



<u>Dimensions</u>: 6.7 meters high; 4 meters wide
<u>Launch Weight</u>: 5,712 kg with propellants
<u>Orbiter science instruments</u>: 12 instruments
<u>Power</u>: 882.1 watts at beginning of mission and 600 watts at end of mission 09/15/2017 from radioisotope thermoelectric generators (RTGs)

Three General Purpose Heat Source Radioisotope Thermoelectric Generators (GPHS -RTGs) on the Cassini spacecraft

Cassini spacecraft and Radioisotope Thermoelectric Generators (RTGs)

Courtesy NASA/JPL-Caltech.

October 9, 1997: At Launch Complex 40 on Cape Canaveral Air Station, workers are installing three Radioisotope Thermoelectric Generators (RTGs) on the Cassini spacecraft. Cassini is undergoing final preparations for liftoff on a Titan IVB/Centaur launch vehicle, with the launch window opening at 4:55 a.m. EDT, Oct. 13

Launch: 4:43 a.m. EDT, Oct. 15, 1997

Cassini spacecraft and Radioisotope Thermoelectric Generators (RTGs)

32.7 kg of plutonium dioxide

82% ^{238}Pu

Produces heat by α–decay into ^{234}U.

Total heat output of all three RTGs: 13.2 kW thermal at BOL. Electrical output was 882.1 W, ➔efficiency was 6.69%.

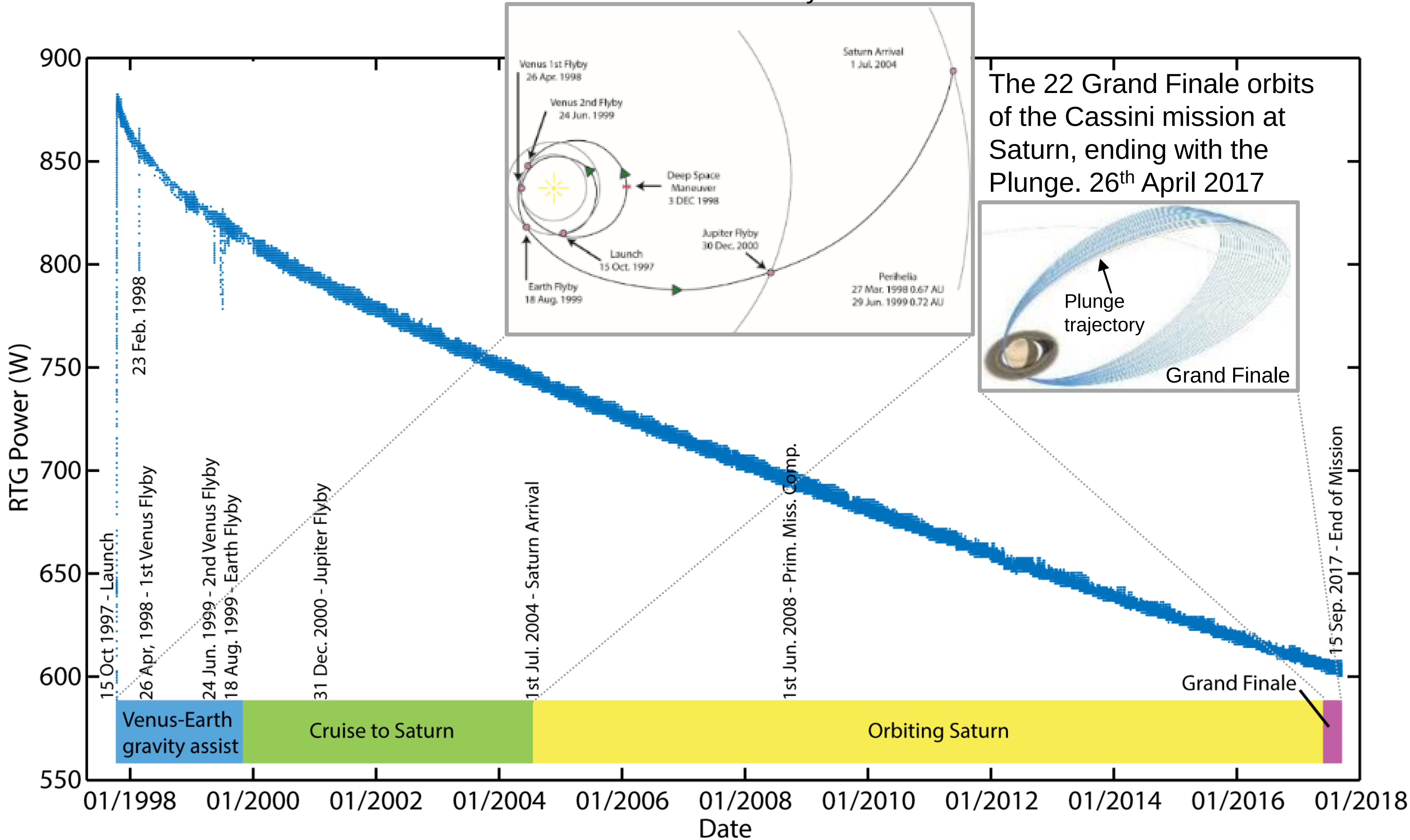
RTGs fuel composition at beginning of life

	RTG 1	RTG 2	RTG 3	Total
^{238}Pu Weight (g)	7693.70	7774.06	7756.40	23224.15
^{239}Pu Weight (g)	1426.55	1447.79	1441.78	4316.11
^{240}Pu Weight (g)	199.87	212.38	202.62	614.88
^{241}Pu Weight (g)	20.24	20.75	20.54	61.53
^{242}Pu Weight (g)	11.84	14.13	12.53	38.50
^{236}Pu Weight (g)	1.07E-04	1.14E-04	1.13E-04	3.34E-04
Total Pu Weight (g)	9352.19	9469.12	9433.87	28255.17
Other Actinides (g)	235.07	166.96	184.74	586.77
Impurities (g)	14.46	15.54	14.26	44.26
Oxygen (g)	1275.94	1243.13	1263.33	3782.40
Total Fuel (g)	10877.65	10894.75	10896.20	32668.60
Pu-238/Total Pu (%)	82.27	82.10	82.22	82.19
Avg. Pellet Weight (g)	151.08	151.32	151.34	151.25
Heat Output (Wt)	4368.06	4413.78	4403.68	13185.52
Avg. Pellet Heat (Wt)	60.67	61.30	61.16	61.04
Avg. Pellet Density (g/cc)	9.83	9.94	9.90	9.89
Activity (Curies)	133934	135368	135040	404342

Astronautics, L.M., *Cassini RTG Program*. 1998.

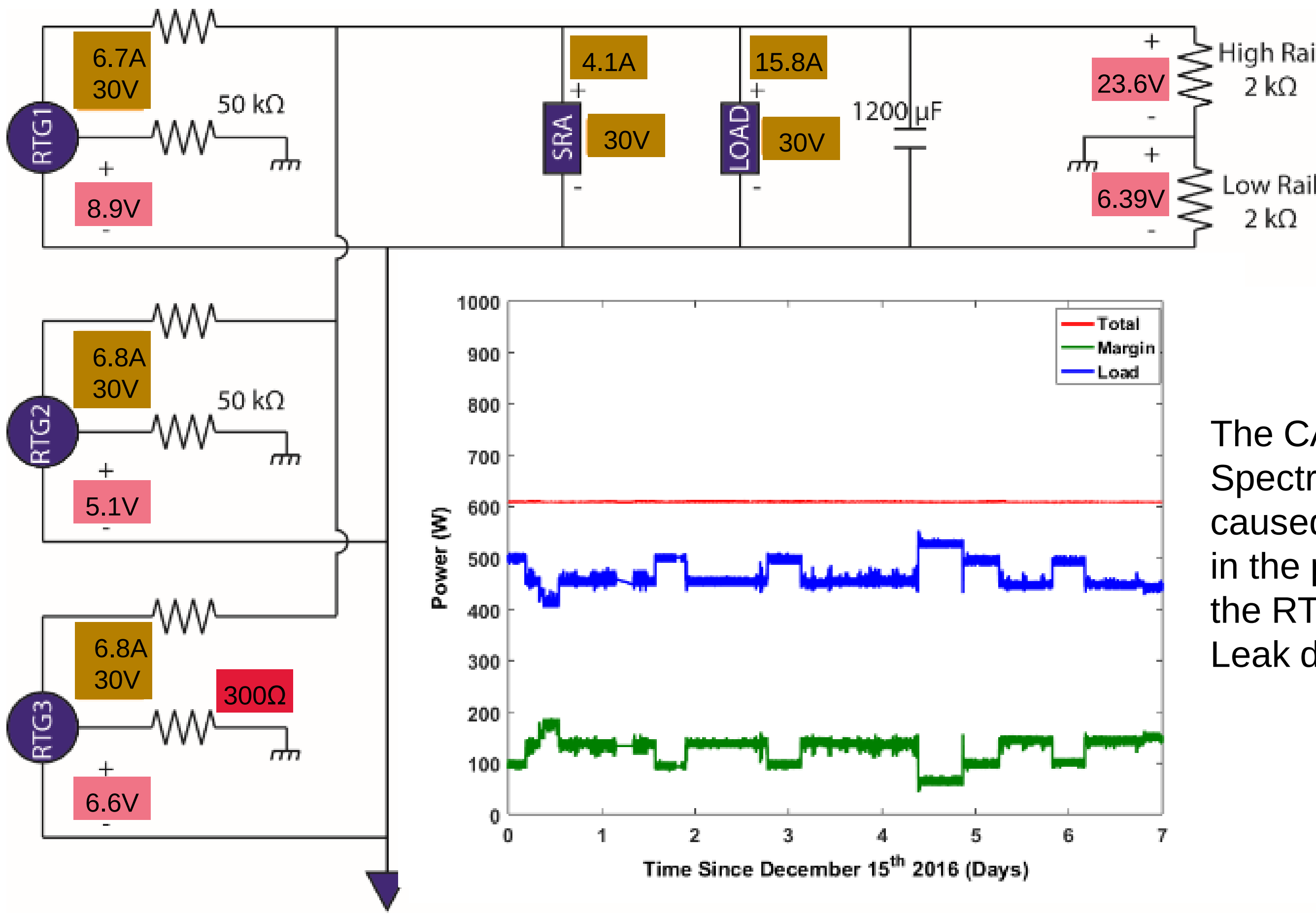
Mission Overview

Cassini's seven-year Venus-Earth gravity assists and cruise to Saturn between launch on 15 October 1997 and Saturn arrival on 1 July 2004.



Cassini Power Subsystem

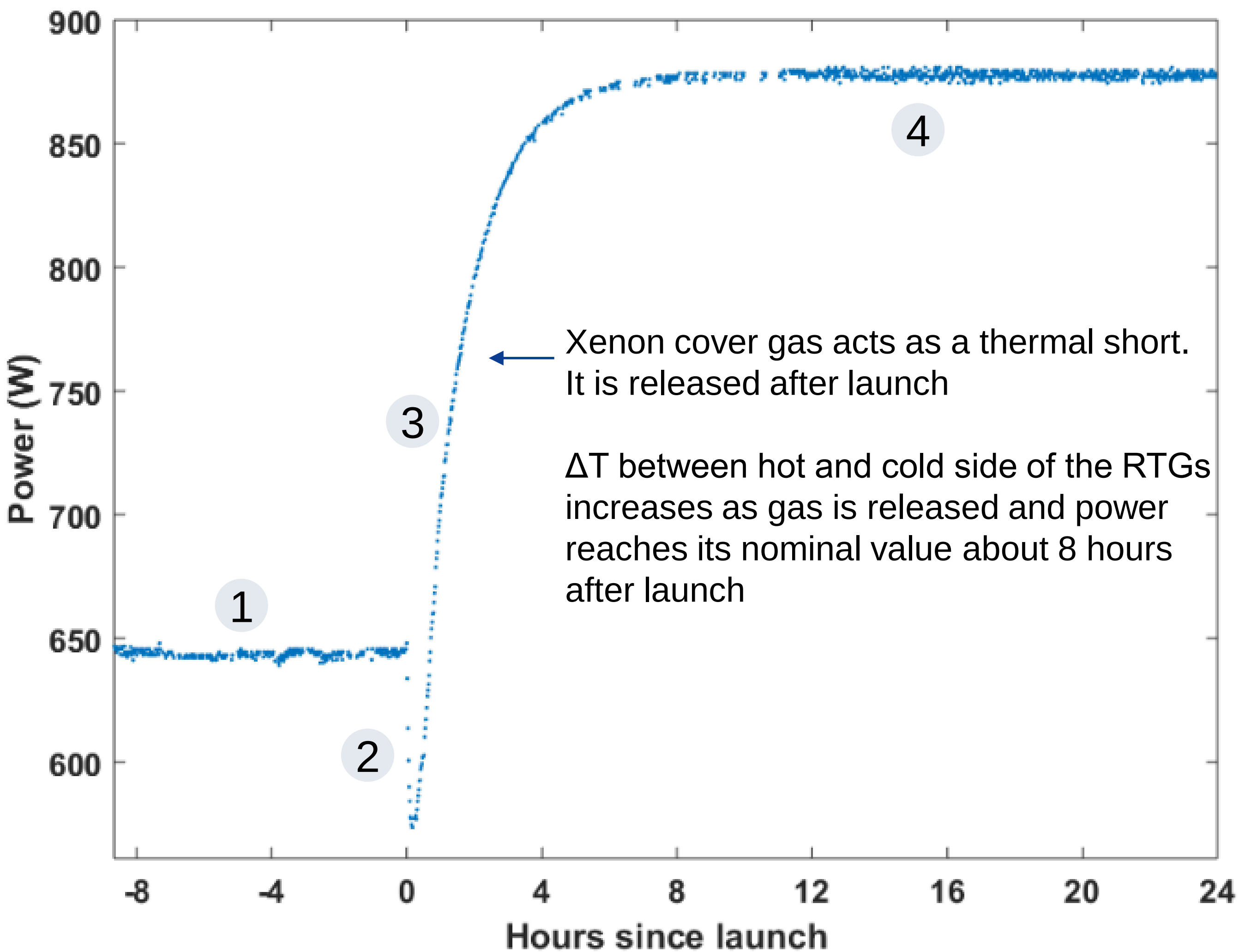
LOAD: series of 192 Solid State Power Switches (SSPS) – not shown



The CAssini Plasma Spectrometer (CAPS) caused a series of shorts in the power bus and in the RTG3 case
Leak due to tin whiskers

- Cassini functional block diagram including RTGs, Shunt Regulator Assembly (SRA) and Load
- Balanced bus divided into two rails: High Rail and Low Rail
- Dual rail design developed by JPL and demonstrated high reliability

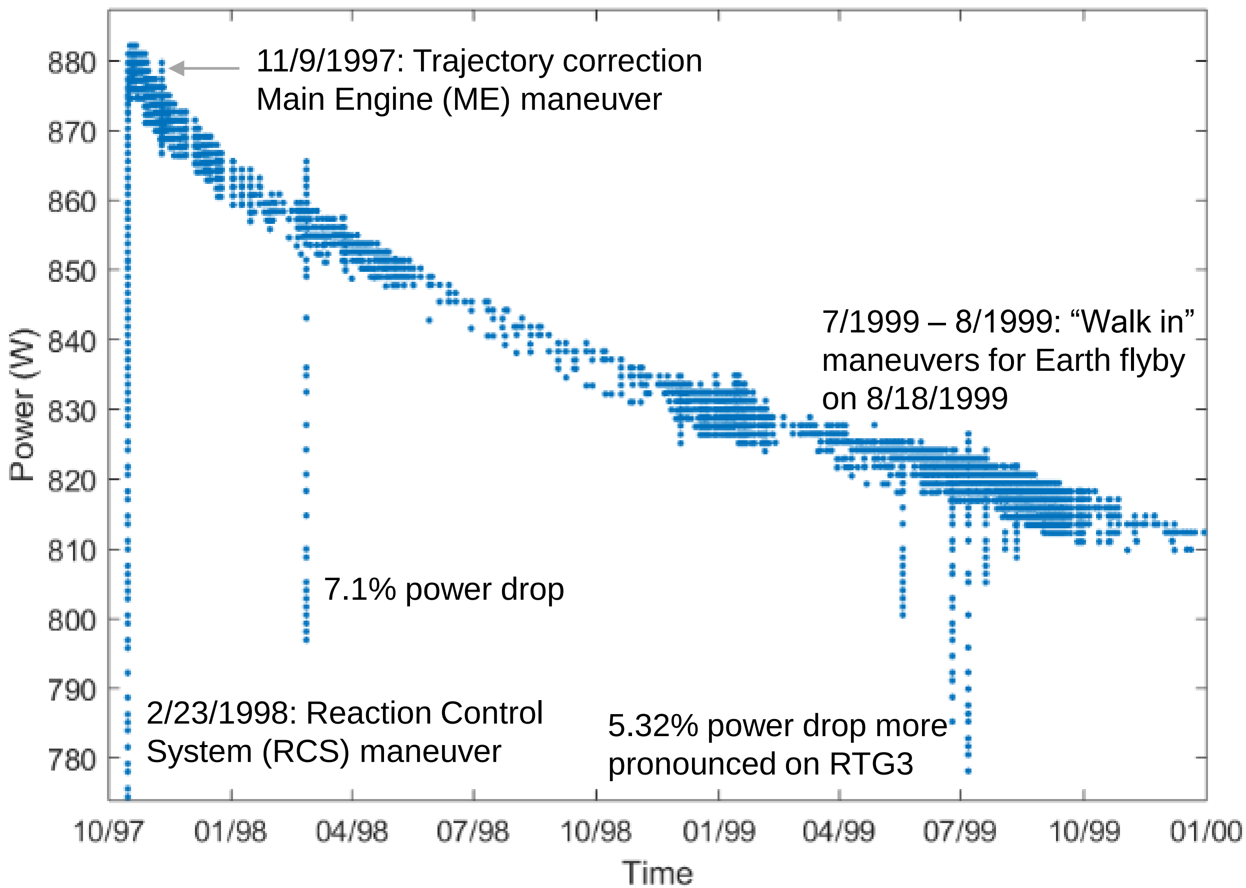
Cassini Power at launch



8:43 a.m. UTC, Oct. 15 1997

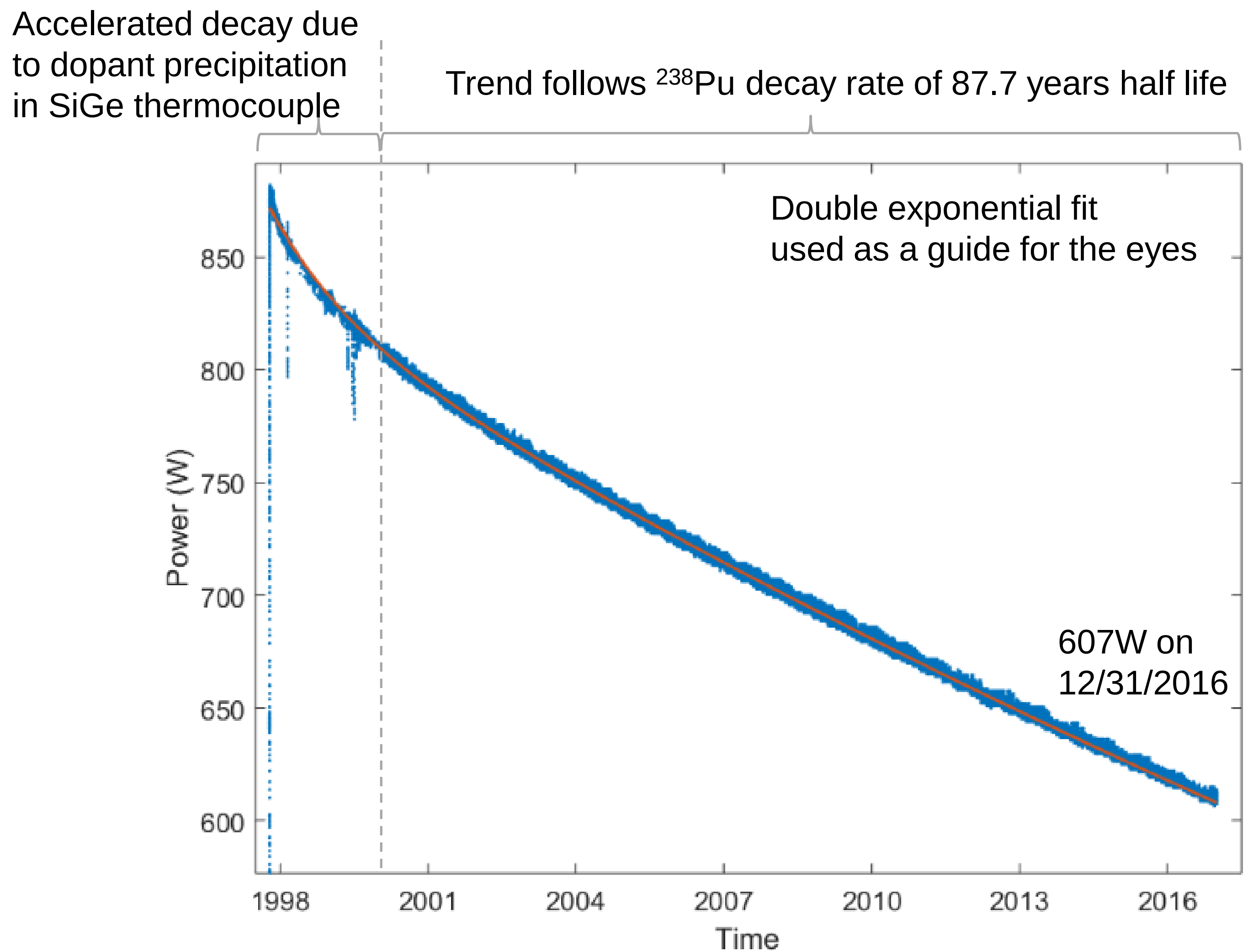
1. Steady state prior to launch
2. After launch: As thermal convection dissipation decreases, cold side temperature increases
3. Xenon cover gas is being released
4. Power reaches its nominal value 882W

Cassini Power over time



Maneuvers executed during Venus-Earth gravity assists had an attitude control variation that exposed the cold side of the RTGs to the sun. This reduced ΔT between hot and cold side of the RTGs and therefore the overall power output.

Cassini Power over time



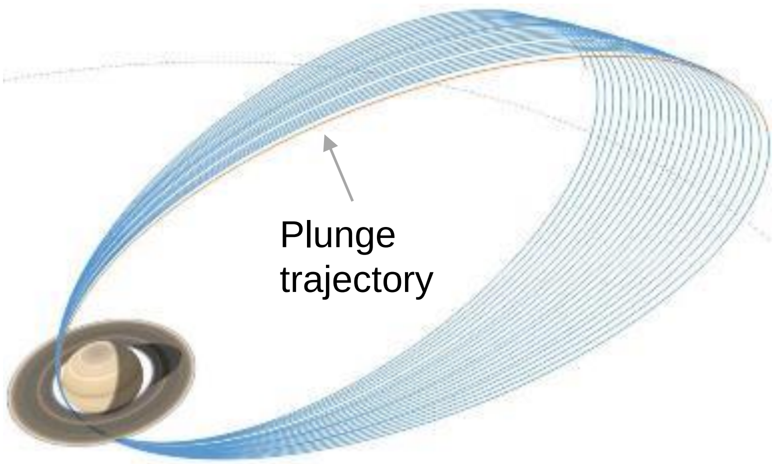
Power at the end of mission 600W on 09/15/2017 Calculated using the "lifetime prediction and performance model".

Actual Power at the end of the mission: 600.3W

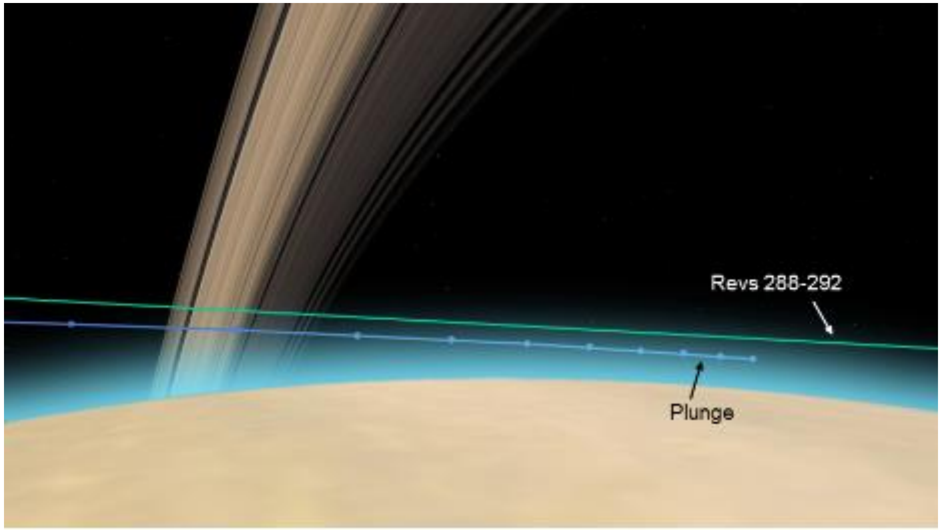
Complete Cassini telemetry data between launch and 12/31/2016

Cassini Grand Finale

The Grand Finale started on 26 April 2017, when Cassini dove in between Saturn's rings and the planet's upper atmosphere for the very first time.

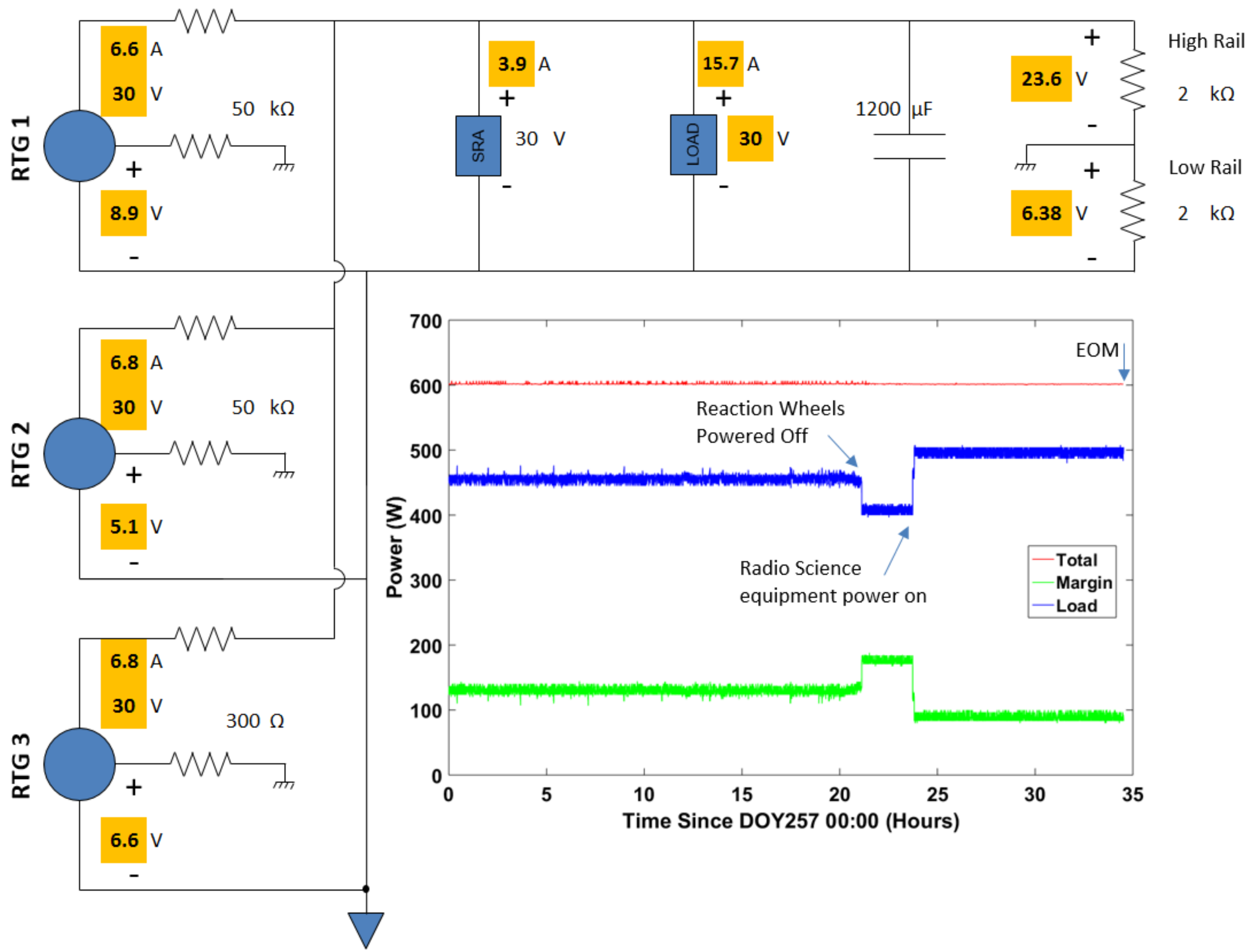


Depiction of the 22 Grand Finale orbits of the Cassini spacecraft at Saturn, ending with the final plunge.



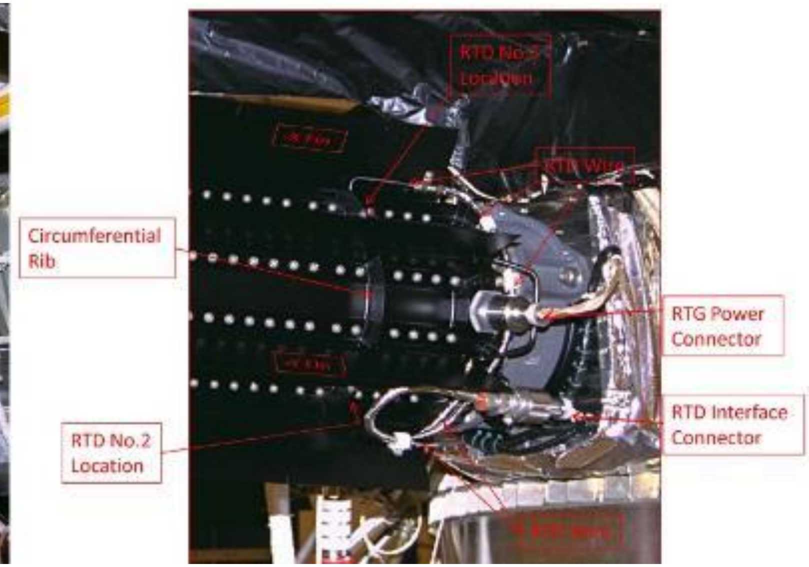
The final five periapsis of the Cassini mission at Saturn. The final plunge occurred on the very next orbit, ending a very successful mission – 15 September 2017.

Last hours of Cassini Power Telemetry

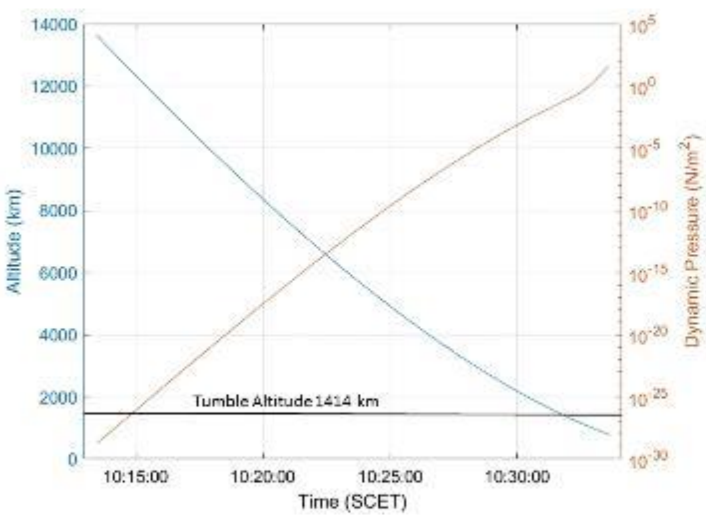


Cassini Power Data during the last hours of the mission until loss of signal

Cassini Last Power, Thermal and Pressure Values

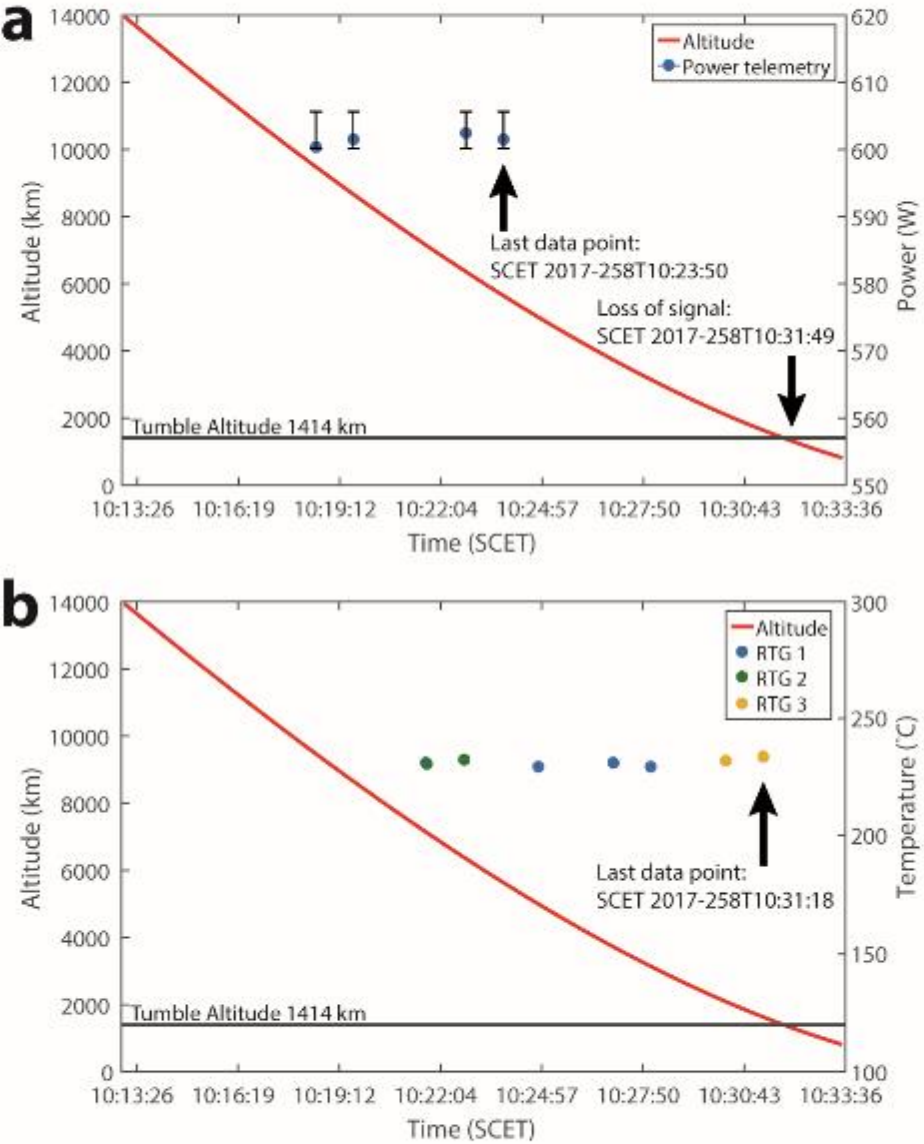


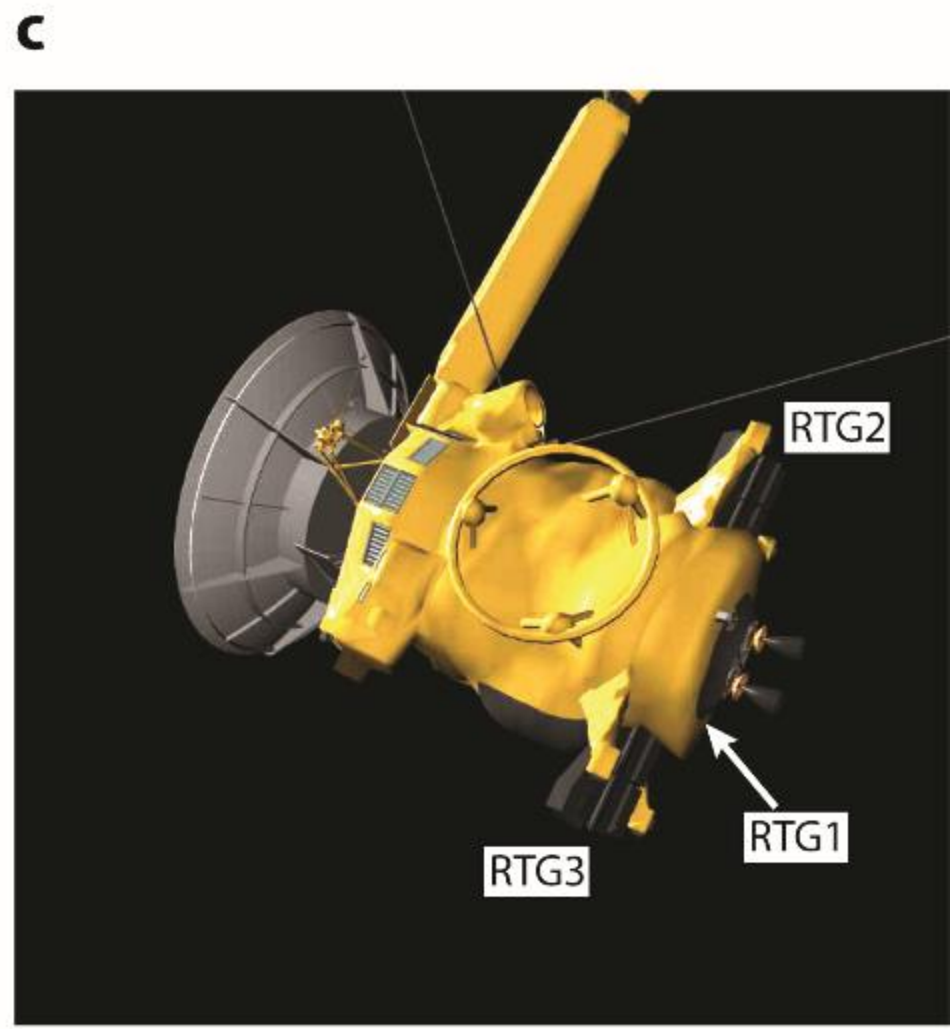
Placement of the Cassini RTG Resistance Temperature Detectors



Dynamic pressure of Cassini compared with altitude above a 1 bar atmosphere. The left hand y-axis is altitude, the right hand y-axis is dynamic pressure as estimated by the Cassini flight team. The x-axis is spacecraft event time (UTC) on September 15, 2017.

Cassini Last Power, Thermal and Pressure Values





Final Plunge: the velocity vector is pointing towards the audience.

Conclusion

- RTGs successfully provided dependable power to Cassini for almost 20 years
- Cassini's balanced bus divided into two rails demonstrated high reliability and electrical shorting tolerance
- Space environmental effects due to spacecraft attitude control had significant impact on power output and later RTG designs
- Cassini's power decay showed 2 very distinct periods
  - Accelerated decay due to dopant precipitation in SiGe thermoelectric elements
  - Exponential decay due to ^{238}Pu decay rate of 87.7 years half life
- As Cassini was entering Saturn's atmosphere, heating of the RTG cases and decrease in power output could have been observed. However, signal was lost before any appreciable heating of the RTG cases or power output decrease had occurred.

Acknowledgements

Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov

This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

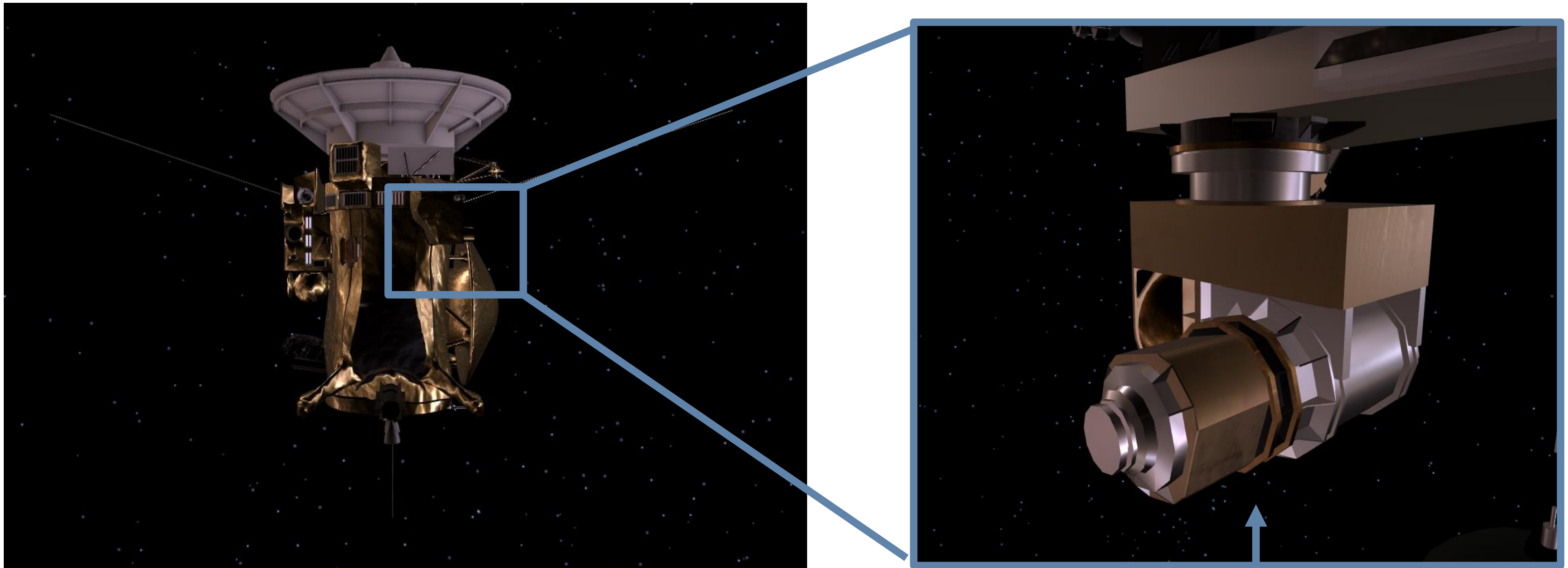
The authors would like to acknowledge the valuable contributions from Terry J. Hendricks, Bill J. Nesmith, Laura Burke and Julie L. Webster.

Picture of Earth from Cassini at Saturn

BACKUP SLIDES

Cassini Plasma Spectrometer (CAPS)

Credit NASA



Cassini's Plasma Spectrometer, called CAPS, is an in situ instrument, detecting and analyzing plasma (ions and electrons) in the vicinity of the spacecraft. Scientists have used the instrument's data to learn about the composition, density, flow, velocity and temperature of ions and electrons in Saturn's magnetosphere.

The Cassini Plasma Spectrometer measures energy and electrical charges

Cassini Plasma Spectrometer (CAPS)

During Saturn tour operations, CAPS experienced a series of short anomalies that affected the power subsystem

28 June 2006: CAPS experienced a series of short accompanied by Low Rail to chassis short that self-cleared within 48 hours. Cause not identified.

30 April 2011: RTG case voltage shifts occurred ➔ Low Rail shifted to 0V and High Rail to 30V ➔ This condition remained for 6 weeks.

11 Junes 2011: High Rail shorted to the chassis ➔ High Rail shifted to 0V and Low Rail to 30V ➔ CAPS was suspected to be involved and 4 days later: CAPS was intentionally turned off. Steady Low Rails 7V, High Rail 23V

Early 2012: NASA Engineering and Safety Center (NESC) conducted an analysis and concluded tin whiskers were the likely cause of the shorts.

18 March 2012: CAPS on, after 2 days bus level changed. RTG overall power decreased by 2W and recovered after a few hours. NESC conducted a 2^{nd} analysis with result that differed from the 1^{st} analysis. Ground testing reproduced internal short scenarios and recommended to turn CAPS off (June 2012). steady Low Rails 6V, High Rail 24V

Power Mission Requirement Discussion

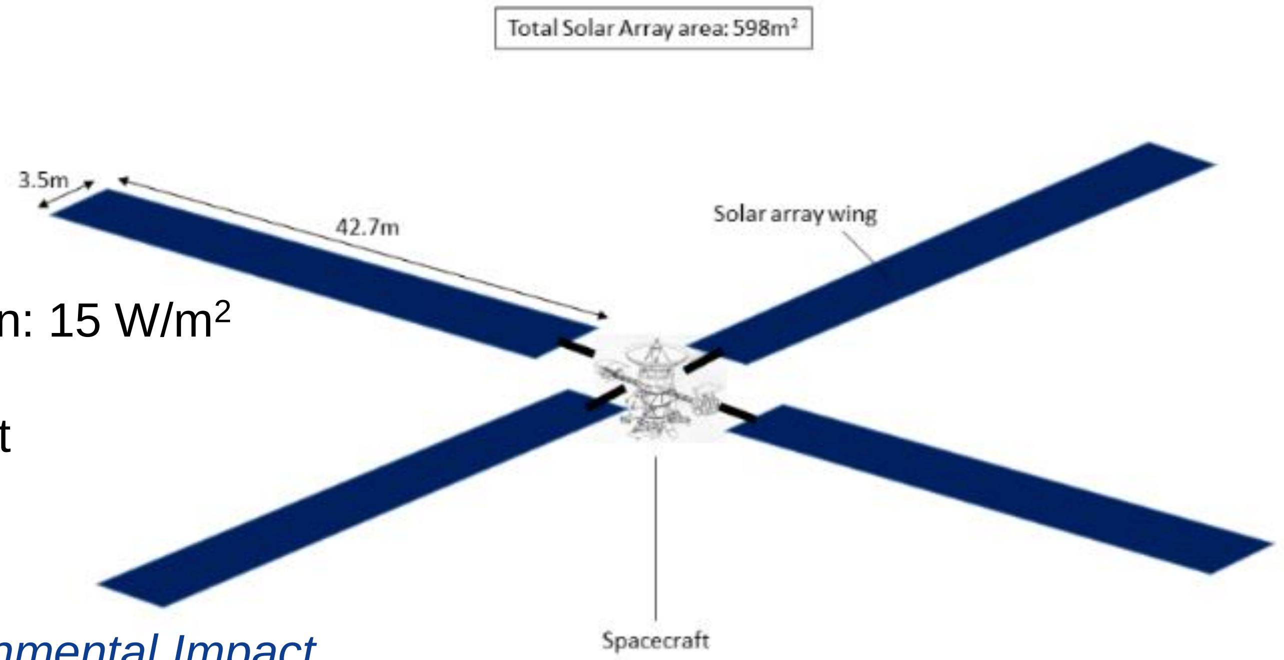
The Cassini power performance over the 20 year lifetime of the mission mimics the historical performance of RTGs for many deep space missions.

RTG: Excellent record in extreme solar range and high radiation environments.

NASA chose to use RTG power for the Cassini mission based on a number of technical factors, including lower mass and improved attitude control compared to necessarily large solar arrays.

Solar cell efficiency has shown steady improvement over the years since Cassini was developed. For 60.35 m^2 solar powered Jupiter mission Juno, limiting radiation degradation and optimizing Low Intensity and Low Temperature (LILT) performance ➔ 416W at end of mission

Power Mission Requirement Discussion



Saturn: 10 AU

Solar intensity at Saturn: 15 W/m^2

Solar intensity (AM0) at earth:1366.1 W/m^2

Cassini Program Environmental Impact Statement Supporting Study. 1994, JPL.

Even with these advances in solar cell/array technology, a Cassini-type mission with a similar science instrument payload would most likely still require a RTG power system solution.

300 m^2 array for a Cassini-like mission with the current solar cell technology